ECOS (European Collaboration On Stable ion beams)

ENSAR NA Report

1. The ENSAR ECOS Network Activity

The ECOS (European COllaboration on Stable ion beams) working group has been appointed by NuPECC in 2004 with the following tasks:

- Describe and access the research perspectives with high intensity stable-ion beams.
- Categorize existing facilities and their possible upgrades.
- Identify the opportunities and specifications for a dedicated new facility in Europe.

The ECOS working group has prepared a report which is available at the NuPECC webpages and which has been published in 2007. One of the important recommendations of the ECOS working group is to ensure a strong support from both the nuclear physics community and the funding agencies for existing stable-ion-beam facilities not only for their accelerator-system development but also for the instrumentation and experimental infrastructure needed to host dedicated research programs. The other important recommendation is that a new dedicated high-intensity stable-ion-beam facility in Europe, with energies at and above the Coulomb barrier, is considered to be one of the important issues to be discussed in the Long-Range Plan of the nuclear physics community. The objectives of the proposed ECOS-Network are related to these two recommendations and they are twofold:

i. Bring together and coordinate the expertise that is available in the European countries in order to achieve the research and development activities in essential aspects related to the production and use of high-intensity heavy-ion beams (Task 1). The important aspect related to the development of high-power ion sources is the objective of JRA01-ARES with which the NA02-ECOS will have a significant synergy.
ii. Optimize resources and manpower for the upgrade and development of various stable-ion-beam facilities in Europe in order to optimize their scientific output (Tasks 2 and 3). From this point of view, NA02-ECOS has a direct link to the TNAs delivering stable ion beams to the users community in Europe. These are TNA01-GANIL, TNA02-GSI, TNA03-INFN, TNA04-JYFL and TNA05-RUG. In order to achieve its goals, NA02-ECOS has been broken down into 4 tasks:

Task 1: *High power thin-target technology (participants: IN2P3 + GANIL+GSI)*

The maximum usable primary beam current with thin targets is among others determined by the long-term stability of the thin targets under irradiation. High beam intensities lead to a considerable heating of the targets, and, hence to thermal stress, possibly phase transitions, oxidation or reduction of the chemical compounds and diffusion into the target backing respectively. We propose to study these phenomena in detail and to compare for example the performance of thin actinide targets as function of the production method (painting, spray-painting, electrolysis, electrode position, evaporation and sputtering), the used chemical compounds (oxide, carbide, others) and backings/coatings respectively. The way is to bring together labs that use different techniques for target preparation and those that can test the target performance under real conditions. For this task ECOS will have the duty to organize the collaboration and exchange of expertise on the development of high power target technology.

Task 2: *Synergies in Superheavy Element Research (participant: GSI + GANIL+JYFL)*

The study of Superheavy Elements (SHE) is one of today's most challenging interdisciplinary research fields. It brings together nuclear physics, atomic physics, chemistry and theoretical physics. Over the last years researchers from the different disciplines have continued to strengthen exchange of ideas. The ECOS community proposes to use this Network in order to enhance synergies among the research groups on a European scale. For this task ECOS is aiming for bringing together the groups with research activities on SHE using high intensity ion beams for an exchange of new ideas and techniques related to the use of very high intensity stable beams.

Task 3: *Organization of bi-annual ECOS Workshops*

In order to optimize resources, two workshops will be organized with parallel sessions dedicated to all aspects of the technical developments and research activities using stable ions beam facilities in Europe. The second workshop will be coupled to the NA town meeting.

Task 4: *Coordination of stable ion beam facilities in Europe and organization of the network*

In order to achieve the goals of the ECOS NA and to foster synergies, collaboration and scientific exchange, a number of meetings have been organized (task 3). This report on task 1 is mainly based on the strategy discussion and in its results performed during the FUSHE 2012 workshop and follow up activities initiated by it. The FUSHE 2012 workshop was held in Weilrod, Germany, from May 13th to 16th 2012 covered all subjects related to superheavy element research including experimental, instrumental and theoretical questions (http://www.ensarfp7.eu/projects/ecos/workshops-meetings/fushe2012). The workshop was attended by about 90 participants from all institutions involved in SHE research worldwide. It was organized in 7 sessions with a strong emphasis on discussions including Theory, Experiment and Instrumentation in an integrated fashion in order to foster a constructive dialogue between theory and experiment. The sessions were organized as a combination of invited talks followed by a topical discussion for the subjects:

- SHE Synthesis
- Nuclear Structure of SHE
- Chemistry
- Atomic Physics and Alternative Approaches,

Covering all three disciplines

- Theory

- Experiment
- Instrumentation.

A document reporting on the findings of this workshop is in preparation and it is briefly summarized in this report. It covers all aspects aimed at by task 1, and will be published in an international peer reviewed scientific journal. This document is being prepared by an international writing group:

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Concerning task 1 a dedicated conference was held during the funding period of the ECOS-NA with the 26th World Conference of the International Nuclear Target Development Society (INTDS 2012) from August 19th to 24th, 2012 at the conference center Erbacher Hof in Mainz, Germany (http://www.intds.org/)

Task3 resulted from a number of meeting and workshop that took place during the funding period of ECOS-NA and in which many the steering committee has played a major role: D. Ackermann (GSI), F. Azaiez (Orsay, Chairman), G. De Angelis (LNL), M. Lewitowicz (GANIL), A. Maj (Krakow), I. Martel (Huelva) and R. Julin (Jyvaskyla).

1. The deliverables:

In the following the three reports corresponding to the three deliverables of the ECOS Network Activities are given:

D-NA02-1: Report on the development of high power thin-target technology with special emphasis on new techniques and methods that will allow increasing the primary beam intensity usable with such targets.

D-NA02-2: Report on the research activities related to SHEs and on the achievement made in this research field

D-NA02-3: Report on the collaborations and synergies between facilities providing stable ion beam facilities in Europe initiated and driven by ECOS network

***D-NA02-2:** Report on the research activities related to SHEs and on the achievement made in this research field*

1. General SHE strategy - "Visions and challenges"

Since the mid-20th century, the synthesis of new chemical elements by nuclear reactions has dramatically expanded the periodic table, from 92 elements in 1940 to 118 today. This increase in the number of observed nuclei has been enabled by a series of advances in nuclear reaction physics, beginning with neutron and light ion bombardment, followed by the cold fusion of heavy nuclei, and most recently by hot fusion experiments using actinide targets. This progress was possible thanks to advances in accelerator technology, high-flux reactors, radiochemistry, particle detection, and nuclear theory. The result has been new understanding of the physics of the atomic nucleus and the chemistry of heavy elements, as well as the production of new elements.

Superheavy nuclei, i.e. nuclei containing 104 or more protons, challenge our fundamental understanding of nuclear structure and stability. Their very existence provides evidence for the shell structure of the nucleus, which conveys stability and increased lifetime to nuclei containing closed shells of neutrons and protons. Many of the neutron-rich superheavy nuclei have lifetimes thousands of times longer than would be expected without this shell stabilization. The evidence points to an increase in lifetime as these nuclei approach the next predicted closed shells, at neutron number N=184 and proton numbers between Z=114 and Z=126. Nuclei in the vicinity of this “island of stability” are likely to have unique nuclear and chemical properties combined with significantly extended lifetimes.

Over the past two decades, significant progress has been made in the journey to the island of stability. Nuclei have been observed with neutron numbers up to 176 and proton numbers up to 118. Experiments aiming at increasing these numbers to N=179 and Z=120, are underway or planned. The powerful accelerators, in operation or under development at JINR in Russia, GANIL-SPIRAL2 in France, RIKEN in Japan, GSI in Germany, and LBLN in the U.S.A., offer the potential to accelerate the discovery and exploration of these extreme nuclei. The ultimate goal is to map the island of stability and produce measurable quantities of new, long-lived superheavy isotopes for fundamental nuclear and chemical studies. This is an exploration unlike any in history, for the prize is finding new nuclei that may not exist on earth or in our solar system, and perhaps not even in the known universe. The physics and chemistry of these new elements will challenge our understanding of extreme nuclear matter and heavy element chemistry, and will open the door to a new materials regime that is both illuminating and revolutionary.

There are many significant challenges that must be addressed to achieve this vision. While substantial progress has been made, the path to significantly higher neutron numbers closer to the center of the island is not obvious. Furthermore, the observed cross sections for the synthesis of superheavy nuclei are very small, and improved production methods and accelerator technology are needed. However, there is much that can be accomplished today with existing capabilities, and much more progress will be enabled by new facilities currently under development. This progress in superheavy element research and discovery will help show the way to the island, providing insights and answers to some of the most fundamental questions in nuclear physics and chemistry with broad implications for both science and technology:

- How many protons and neutrons can a nucleus hold together? What is the heaviest element that we can synthesize today and in the future? Where is the end of the periodic table in atomic number and mass?
- Can we develop a comprehensive theory of nuclei from the lightest to the heaviest? Are superheavy nuclei fundamentally different, and do they represent a new state of nuclear matter?
- What are the properties and boundaries of the predicted “island of stability” for superheavy elements? Does the stabilization emerge without large energy gaps?
- How can we produce superheavy nuclei that are more neutron rich?
- What is the physical and chemical behavior of elements with extreme numbers of neutrons, protons, and electrons?
- Can we understand the details of the fission process and competing decay modes?
- Can we understand and optimize the production mechanisms for superheavy nuclei: hot and cold fusion, multi-nucleon transfer, etc.? Can we produce measurable quantities of superheavy elements?
- Do superheavy elements exist in the universe, and how are they produced? Are there remnants of long-lived superheavy elements on earth?

2. Production of SHE and reaction dynamics

Up to date complete fusion reactions followed by particle evaporation was the only successful reaction scheme leading to the synthesis of nuclei with possibly up to 118 protons. This process is often modeled as a two/three-step process. It consists of the formation of a compound nucleus (CN) in a heavy ion collision which is often described separately by the so-called capture with a possible subsequent compound nucleus formation which is then followed by the de-excitation of the hot ensemble via nucleon and photon emission. The competition of fusion with the various alternative reaction channels in heavy ion collisions as well as the survival against fission in the cooling process of the excited compound system determines the probability for a successful synthesis of a superheavy nucleus (SHN) in such a reaction. In the entrance channel, fusion-evaporation has to compete with elastic and inelastic collisions, and fast or quasi-fission, all leading to direct re-separation of the heavy nuclear system.

The large value of the product of the nuclear charge of projectile Z_p and target Z_t together with the low fission barriers of those heavy systems, which are of the order of and even smaller than the neutron separation energies, lead to a narrow band of excitation energy for which the eventual CN formation is possible. In experiments two approaches, the so called cold and hot fusion reactions, are pursued, using suitable projectile-target combinations, to synthesize SHN, discriminated by modestly different ranges of excitation energies $E*$ of the formed systems. Cold fusion reactions employing ^{208}Pb and ^{209}Bi were used to produce SHN from Z=107 to 112 and 113. In the exit channel of the reaction particle evaporation, cooling the nucleus to a temperature below the fission barrier to eventually form a surviving evaporation residue after additional γ emission to the ground state or an isomeric state, has to compete with compound nucleus fission.

The investigation and quantitative understanding of both phases of the synthesis process is essential for a successful progress towards the discovery of nuclei with even higher Z and eventually the discovery of the long sought for "island of stability". For the entrance channel and the investigation of the barrier details determining the amalgamation of projectile and target, classically precise fusion excitation functions with small steps in kinetic energy have been employed to extract an experimental representation of the fusion barrier distribution. This method, however, is presently limited to reactions with rather high cross sections due to the required high counting rate. To push its applicability high beam currents are clearly desired. As an alternative approach to get investigate the fusion barrier the employment of the partial wave distribution has been proposed.

Alternatively to fusion the process of nucleon transfer in damped collision of very heavy partners, including the heaviest species available for projectile and target preparation like ^{238}U, could lead in its high A and Z tail to the production of superheavy nuclei. As in fusion reactions with stable beams the region of spherical shell stabilized superheavy nuclei cannot be reached, this method could be a possibility to accomplish their synthesis, although with probably extremely low production probabilities. A test measurement in a lighter mass region for the colliding system ^{160}Gd + ^{184}W, employing a rather simple experimental set-up, showed not only the feasibility of such types of studies. In addition enhanced yields for trans-target reaction products as compared with the predicted yields had been observed. The understanding of the nucleon transfer process itself is essential for both, its possible exploitation for SHE synthesis as well as for the understanding of its role in competition with the fusion evaporation process. Beam intensity is also here a major issue to extend the existing knowledge. The only other envisioned production scheme, the complementary use of unstable neutron rich projectiles, provided by the next generation radioactive beam facilities, suffers still from by far too low beam intensities.

3. Nuclear structure of SHE

The strong nuclear force is one of the four basic interactions. It played and still plays an essential role in the development of the universe, not only in the early phase, where the quark-gluon plasma was prevailing, but also for the formation and development of stars, the synthesis of the chemical elements and the structure of atomic nuclei. The latter aspect had been neglected for a long time as many models treated the nucleus as an ensemble of approximately quasi-free, not interacting nucleons, i.e. protons and neutrons, moving in a mean potential. On this basis it was argued that the structure of the nuclei would not provide notable information about the nuclear force and thus the strong force.

The emergence of new theoretical approaches to describe properties of heavy nuclei during the past two decades, however, compels us to change this point of view. Self-consistent calculations using different functionals for describing the nucleon – nucleon force (or interaction) disagree in predicting properties of heaviest nuclei while they sufficiently agree in the region of medium heavy nuclei, e.g. around Z = 50, N = 50, 82. Conclusion of these facts is that properties of superheavy elements are more sensitive to subtleties of the nuclear force. This is not so surprising as their existence is only due to a subtle balance between nuclear forces and Coulomb forces. Superheavy nuclei therefore provide an important laboratory to study the nuclear forces, which show up in many facets as ground-state masses, ground state deformation, decay properties, nuclear structure, which also comprises the occurrence and strength of spherical and deformed proton and neutron shells. So a thorough investigation of all these aspects will provide a more detailed insight in the nature of the strong force and thus contribute essentially not only to understand the micro-structure (micro-cosmos, atomic and subatomic dimensions) but also the macrostructure (cosmic dimensions, macro-cosmos) of our world.

Last but not least it should be mentioned that the strong force not only influences the structure of the nuclei but also the interaction of two nuclei approaching to distances where nuclear forces become essential; in other words, the strong force has also a significant impact on the formation probability of superheavy nuclei. Thus studies of reaction mechanisms are additional sources for information on the nature of the strong force.

From the experimental side exploring the neutron shell at N = 184 suffers from practical difficulties as it cannot be reached in vicinity of the predicted proton shell (Z = 114) in complete fusion reactions using any combination of stable projectiles and available target nuclei. More neutron-rich projectiles are required. Presently available RIB facilities, however, deliver beam intensities many orders lower than required for synthesis of SHN in notable irradiation times. New, more powerful facilities are required. Nevertheless it is expected that information concerning localization and strength of the above mentioned shells can be obtained by extrapolation of nuclear properties from the known region. Experimental data on decay properties and nuclear structure can be used to test and to improve nuclear models leading to qualitatively better predictions on the "island of stability", its location, its extension and properties of nuclei in that region.

To meet this goal a world-wide extensive program on investigation of nuclear structure of SHN has been started including scientists from the major facilities in Europe with GSI Darmstadt, HIM Mainz, GANIL Caen, CSNSM Orsay, IRFU Saclay, IPHC Strasbourg, JYFL Jyväskylä, University of Liverpool, U.S.A. and Asia.

4. Instrumentation

The manifold challenges created by the aim of pushing the field to its extremes in mass, atomic charge and isospin, and consequently cross section, sensitivity and complexity demands for high-end technology for all instrumentation components involved. Intensity is the key governing all activities in accelerator development. Target technology has to cope with the high projectile rates and the special requirements needed in handling of stable and exotic, actinide materials under these conditions. Sensitivity, separation and correlation determine the efforts dedicated to future separators, spectrometers and detection set-ups. And finally new approaches, employing techniques developed and applied in other disciplines like atomic physics, open new avenues to investigate the basic as well as exotic features expected for the species in the focus of SHE studies.

The part related to the high power target technology and developments is described in a dedicated report **D-NA02-1,** we therefore concentrate here on the accelerators developments and strategy which is illustrated through mainly three major projects:

4.1. Accelerator projects at GSI

An upgrade program of the existing GSI Universal Linear Accelerator (UNILAC) has to be realized in the next years, such that enhanced primary beam intensities at the experiment target are available. For this a new super-conducting (sc) 28 GHz full performance ECR ion source is under development. Via a new low energy beam line an already installed new RFQ and an IH-DTL will provide for continuous wave (cw) heavy ion beams with high average beam intensity. Together with a new cw heavy ion linac added to this high charge state injector is planned to form a new dedicated high intensity/high duty cycle accelerator facility for SHE research, with SHIP and TASCA, as well as material research, biophysics and plasma physics experiments at beam energies of several MeV. The linac will be integrated in the GSI-UNILAC-environment.

The technical design and the realization of such a sc cw-linac in parallel to the existing UNILAC at GSI is assigned to a collaboration of GSI, the Goethe University Frankfurt (Institute of Applied Physics) and the Helmholtzinstitut Mainz (HIM). A conceptual layout of a sc cw-linac was worked out, which allows the acceleration of highly charged ions with a mass to charge ratio of 6 at 1.4 MeV/u from the upgraded high charge injector (HLI) of UNILAC. Nine superconducting CH-cavities operated at 217 MHz accelerate the ions to energies between 3.5MeV/u and 7.3MeV/u, while the energy spread should be kept smaller than $\pm$3keV/u. As beam focusing elements seven superconducting solenoids are implemented. The first section of the cw-linac comprising a sc CH-cavity placed in between two sc solenoids (financed by HIM and the Helmholtz Portfolio Initiative Accelerator Research and Development) as a demonstrator will be tested with beam at the HLI of UNILAC at GSI in 2015. After successful testing the construction of an advanced cryogenic module comprising four CH cavities is foreseen. As an intermediate step towards a complete cw-linac, the use of a doublet of two CH-cavities is planned: a short 5 cell cavity should be mounted directly behind the demonstrator cavity inside a short cryostat. The design of the cw-linac based on shorter sc CH-cavities would minimize the overall technical risk and costs. Besides with this cavity an optimized operation of the whole linac especially with respect to beam quality could be achieved. Last but not least the concept of continuous energy variation applying phase variation between the two cavities with constant beta profile could be tested. Successful R&D at the cw-CH-linac demonstrator is a milestone for the realization of the sc-cw-linac-project.

This new injector linac could be an integrated part of a revised multipurpose heavy ion linac at GSI. A proposal for this advanced GSI-injector environment including all beam transfer lines was elaborated in 2011. Beam could be delivered by the cw-linear accelerator for highly charged ions and by the synchrotron injector (HE-linac) on a pulse to pulse basis. Then the warm cw-linac (HLI) in combination with the HE-linac could also serve as a synchrotron injector for rare isotopes delivered by the ECR-ion sources. Optionally heavy ions, mainly uranium ions, from the high intensity injector of HE-linac HSI would be transferable to the cw-linac (cold), where a high duty factor ion beam could be accelerated for UNILAC experiments (e.g. for the material research cave). After completion of the technical design in the next three years, the HE-linac will be gradually built up until 2022.

4.2. Accelerator projects of FLNR

As one of the most advanced upgrade projects in SHE research, a new project aiming at high production rates of SHN is presently under construction at the FLNR of the JINR in Dubna. The heart of the so-called SHE factory is a new high intensity accelerator. The DC280 cyclotron is planned to deliver beams of 5-8Mev/u at intensities of 10-20 particle μA. This dedicated facility is foreseen to operate 7000 h per year delivering a total dose of 1.3×10^{21} projectiles, a factor of $\approx$ 30 more than presently achievable at FLNR. Assuming a state of the art separator and detection system, the facility should yield a total production of $\approx$5000 decay chains per year originating from SHN with typical production cross sections of 1-10 pb, thus allowing for a wide science program going beyond the pure production and including detailed spectroscopy of the decay properties of SHN.

4.3. LINAG and the Super-Separator-Spectrometer at GANIL-SPIRAL2

The heart of the SPIRAL2 facility at GANIL, the superconducting Linear Accelerator (LINAC), presently under construction, will deliver highly intense (5-10 particle μA) beams in the Coulomb barrier energy regime, from deuterons to heavy ions. These unprecedented intensities, combined with the Super Separator Spectrometer (S^3) which is designed for fundamental physics experiments, will open new horizons of research in the domains of rare nuclei and low cross-section phenomena at the limit of nuclear stability.

S^3 will provide a very high acceptance while keeping an excellent mass resolution. This will be achieved with innovative superconducting magnetic triplets in order to correct optical aberrations. Moreover, the use of radioactive actinide targets included in the project will make this facility competitive in the field of SHE research. The detection system at the focal plane is developed for alpha, electron and gamma spectroscopy complying with the needs of decay spectroscopy of exotic species. A gas catcher system will be available to make those exotic nuclei available for low energy techniques like e.g. precise mass measurements and laser spectroscopy.

Although S3 is designed for a wide range of physics cases, its performance has been optimized more specifically to answer the need of experiments aiming at decay studies of nuclei produced by fusion evaporation reactions, mainly in the domain of superheavy species and for proton drip line nuclei.